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Chemical and Physical Studies of Type 3 Chondrites—XI: Metamorphism, Pairing, and Brecciation of Ordinary Chondrites

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Induced thermoluminescence (TL) data for 69 type 3 ordinary chondrites have been obtained. With updated literature data, this brings to 125 the number of type 3 chondrites for which TL data are available, probably around 106 when pairing among Antarctic samples is taken into account. The data are used, with literature data for olivine heterogeneity, carbon content, and inert-gas content, to assign the meteorites to petrographic types. Brecciation is common among type 3 ordinary chondrites, and petrographic and inert-gas data indicate that several are regolith breccias. However, it is unusual for clasts from a single breccia to differ by more than 0.4 in petrologic type. In agreement with earlier work, the new data produce two clusters on a TL peak temperature vs. TL peak width plot, with type 3.2-3.4 tending to plot in one cluster and type 3.6-3.9 in the other. The implications of this clustering for paleotemperatures have been previously discussed, and recent data from other paleothermometry techniques generally confirm the temperatures of 500°-600°C for type 3.5 suggested by the TL data. H3 chondrites show higher TL sensitivities than L3 and LL3 chondrites, so that most of the type <3.4 samples are L or LL chondrites, while, except for two splits from the ALHA81251 breccia (one of type 3.2 and one of type 3.4), the most primitive H chondrite is type 3.5. This trend is probably not due to different accretion times or burial depths, but is due to differences in the physical properties of the three classes. Differences in physical properties may be more important than accretion times and burial depths in determining the thermal history of chondrites.

INTRODUCTION

The ordinary chondrites referred to as "type 3" by *Van Schmus and Wood* (1967) and "unequilibrated" by *Dodd et al.* (1967) are the least-metamorphosed members of the three ordinary chondrite groups. They afford a unique opportunity for exploring preplanetary processes and for distinguishing the effects of processes that occurred prior to aggregation from those, such as parent-body metamorphism, that occurred subsequently. However, the type 3 chondrites show a broad spectrum of metamorphic alteration (*Wood*, 1967; *Dodd et al.*, 1967; *Sears et al.*, 1980; *Afiattalab and Wasson*, 1980; *Huss et al.*, 1981), and it has proved helpful to assign them to petrographic type 3.0-3.9. Particularly useful in ranking meteorites by metamorphism is thermoluminescence (TL) sensitivity, which increases by a factor of 10^5 as the level of metamorphism experienced increases from type 3 to type 6 (*Sears et al.*, 1980). This is apparently because metamorphism caused the production of feldspar by the devitrification of primary feldspathic glass (*Guimon et al.*, 1986). The same, or a closely related, process can be observed petrographically using the cathodoluminescence microscope (*DeHart and Sears*, 1986; *Sears et al.*, 1989).

It is also of interest to try to quantify the conditions under which metamorphism occurred, namely peak temperatures experienced during metamorphism, equilibration temperatures (these are often assumed to be the same), and postmetamorphic cooling rates. Such parameters provide clues to parent-body sizes, parent-body structures, whether metamorphism occurred in hard rock or a regolith, burial depths, and the heat source for metamorphism. However, the available methods for evaluating the thermal history of rocks have proved difficult to apply to type 3 ordinary chondrites, mainly because of their lack of equilibration. Some of the most useful information is derived from metal and associated phases (*Wood*, 1967; *Rambaldi and Wasson*, 1981), while pyroxene phase relationships and compositions provide some clue to metamorphic conditions (*Dodd*, 1969; *McSween and Patchen*, 1989). *Wlotzka* (1985, 1987) has shown that metamorphic temperatures can be derived for the high petrographic types from the Cr-spinel/olivine geothermometer. Most recently, *Brearley* (1990) has determined paleotemperatures using a geothermometer based on the graphitization of carbonaceous material. *Guimon et al.* (1984, 1985) found that induced TL data also provide constraints on metamorphic temperatures, and perhaps also cooling rates (*Keck et al.*, 1986). Ordinary chondrites of type 3.2-3.5 produce glow curves of a different shape than those of type 3.6-3.9, and a comparable range of glow curve shapes can be produced by laboratory heating experiments. *Guimon et al.* (1985) argued that the changes are indirectly related to disordering of ordered feldspar and that the type 3.5 corresponds to temperatures near the order/disorder transformation temperature, which they presumed to be 500°-600°C.

Complicating the picture is brecciation. Many type 3 ordinary chondrites are known to be breccias (*Keil*, 1982; *Scott et al.*, 1985b). There are also meteorites that are rich in trapped solar gases and charged-particle tracks due to solar flares, and in these cases brecciation appears to be associated with a prolonged period of regolith activity (e.g., *Pellas*, 1972). Identification of the extent of brecciation among the type 3 chondrites in general, and identifying the individuals that appear to be particularly brecciated, is of considerable value in deciphering the history of these meteorites. Other important questions concern the timing of metamorphism in relation to brecciation and the extent to which individual components (e.g., chondrules) were metamorphosed prior to being incorporated in the meteorite (*Dodd*, 1968, 1971, 1978; *Scott*, 1984a; *Sears et al.*, 1984b). For most type 3 chondrites there is a simple relationship between TL sensitivity, carbon, and inert-gas contents, since metamorphism caused increases in TL sensitivity and loss of volatile elements and carbon. (More complicated explanations for this relationship have also been discussed, e.g., *Anders and Zadnik*, 1985.) However, a few ordinary chondrites appear to be anomalously rich in these elements. *Anders and Zadnik* (1985) suggested that these anomalous meteorites are different forms of primitive material, but we argue below that they are also the result of brecciation.

Another complicating factor in looking for trends or distributions of data among type 3 chondrites is that most are from the Antarctic, and separate meteorites may actually be fragments of the same fall (i.e., "paired"; *Scott*, 1984b, 1989). Care must therefore be taken to ensure that possibly paired meteorites are identified and their data averaged on the appropriate plots.

The present paper reports new measurements of the induced TL properties of 69 type 3 ordinary chondrites and brings to 125 the number of type 3 ordinary chondrites for which TL data are available (probably around 106 when pairing among Antarctic meteorites is taken into account). The paper is a continuation of those of *Sears et al.* (1980, 1982) and *Sears and Weeks* (1983). Among the present samples are several of particularly low petrographic type and many breccias, some of them gas-rich. We also discuss the significance of the data with respect to the physical conditions affecting metamorphism and the issues mentioned above.

EXPERIMENTAL

The samples, their sources, and other information are listed in Table 1. Since type 3 ordinary chondrites are not only heterogeneous but are sometimes breccias, two chips were generally obtained, taking care to sample different lithologies when present. In several instances, the samples were sent to us by groups who have performed complete mineralogical and petrological studies. [ALHA77176 and ALH77050, *Scott*, 1984a; Suwahib (Buwah), *Scott et al.*, 1985a; Inman, *Keil et al.*, 1978; Ragland, *Recca et al.*, 1986; Bremervörde, *Sears and Weeks*, 1983; Villa Natamoros, *Hewins et al.*, 1988; Carlisle Lake, *Weisberg et al.*, 1989; Gunlock, *Prinz et al.*, 1988; Julesburg, *Graham and Huss*, 1986; Willaroy, *Chalmers and Mason*, 1977; Dimmitt, Grady (1937), and Julesburg are from the study of SiC in chondrites by *Huss and Lewis*, 1989; Ceniceros and St. Rose are from current studies by A. Graham and C. Caillet, respectively; and B. Mason has much unpublished data on Moorabie, Quinyambie, and Starvation Lake.] Sample masses were generally 50-300 mg, from which 4 mg of nonmagnetic, homogenized 100-mesh powder was used for the TL measurement. Three to five curves are recorded for each powder, and quoted uncertainties are standard deviations calculated from these replicates. (A preliminary version of about half the new data was presented, without discussion, in a survey by *Sears and Hasan*, 1987.)

For the present measurements we used two high-sensitivity TL systems manufactured by Daybreak Nuclear and Medical Systems Inc. These use EMI 9635 photomultiplier tubes, with Corning 7-59 and 4-69 filters to suppress black-body radiation, and photon-counting electronics. The addition of shutters and other modifications enables the high voltage to be left on throughout the measurements, metering valves enable high-purity N_2 to be bled into the glow oven, silica gel in the PMT housing suppresses dark current, and data are gathered automatically on Texas Instruments personal computers using custom-made interfaces and software. Two Sr-90 beta sources are used for the standard irradiations; both result in absorbed dose rates of ~1 krad/min. The Dhajala meteorite is used as a day-to-day and long-term standard to monitor the apparatus and procedures and to provide a basis for interlaboratory comparison. The maximum light produced (TL sensitivity, normalized to Dhajala), the temperature of maximum light production ("peak temperature"), and temperature range over which light is produced (more precisely, the full-width at half-maximum for the TL peak, or "peak width") are measured (*Sears and Weeks*, 1983).

The data reported here were obtained between early 1984 and late 1989 and there have been many improvements in our techniques during that period. For this reason, repeat measurements were occasionally made on samples for which we have already published data; these were included in the averages in Table 1. We found that the pans in which samples are placed for TL measurement can cause a temperature lag between the sample and the heating strip. In our apparatus, temperature is measured by a chromel-alumel thermocouple spot-welded to the underside of the heating strip. We have attempted to correct for this temperature lag by comparing the known melting points of material from a series of "Tempilstik" pens heated in the pans, with the temperature indicated by the apparatus. Temperature lag results in peak temperatures and widths being overestimated by 5°-20°C, but has negligible effect on TL sensitivities.

RESULTS

Table 1 is an updated list of induced TL data for type 3 ordinary chondrites. We will first look at the data with a view to identifying paired Antarctic meteorites, then consider possible brecciation effects and instances of excess volatiles discussed by *Anders and Zadnik* (1985), then finally determine petrographic classification.

Pairing

Ten groups of paired type 3 ordinary chondrites have been suggested in the literature; these involve meteorites from Allan Hills, Lewis Cliff, Reckling Peak, and South Australia.

Allan Hills. *Scott* (1989) lists 76 Allan Hills type 3 meteorites that he suggests are all fragments of a single meteorite, and Mason has tentatively added ALH83038 and

TABLE 1. Induced thermoluminescence data for type 3 ordinary chondrites.

Meteorite†	No. Splits	TL Sens. (Dhajala=1)‡	Peak Temp. (°C)‡	Peak Width (°C)‡
ALHA76004,12	1	0.012 ±0.006	94	—
,14	1	0.055 ±0.016	79	91
ALHA77011	2	0.3 ±0.1	101±21	102±12
ALHA77013	1	0.14	119	151
ALHA77015	2	0.17 ±0.02	108±6	97±12
ALHA77050	1	0.24 ±0.08	114±1	94±6
ALHA77167	1	0.07 ±0.01	106±1	92±16
ALHA77176	1	0.01	87	107
ALHA77197	1	0.38	139	—
ALHA77214	2	0.07 ±0.03	106±4	89±6
ALHA77216,wht clst	1	2.4 ±0.1	139	142
,bulk	1	0.74 ±0.18	146	145
ALHA77249	2	0.08 ±0.03	106±5	94±4
ALHA77260	2	0.12 ±0.02	100±13	98±5
ALHA77278	2	0.25 ±0.14	151±7	151±7
ALHA77299	2	0.47 ±0.31	151±7	151±7
ALHA77304	2	0.60 ±0.03	147±4	179±6
ALHA78038	2	0.08 ±0.04	105±5	114±6
ALHA78041	2	0.066 ±0.009	103±6	75±8
ALHA78084	2	2.3 ±0.2	175±18	104±14
ALHA78119	2	0.10 ±0.03	118±4	97±6
ALHA78133	1	0.10 ±0.02	112±10	81±1
ALHA78138	2	0.11 ±0.04	122±17	107±19
ALHA78162	2	0.06 ±0.01	120±4	98±9
ALHA78176	2	0.04 ±0.01	114±2	91±3
ALHA78180	2	0.060 ±0.008	117±6	102±15
ALHA78235	2	0.05 ±0.01	108±8	85±2
ALHA78239	2	0.05 ±0.01	112±4	83±7
ALHA79022	1	0.96	141	147
ALHA81024	2	0.18 ±0.04	141±6	143±4
ALHA81025	1	0.35 ±0.04	167±8	129±7
ALHA81030	2	0.081 ±0.002	112±8	77±5
ALHA81031	2	0.06 ±0.02	96±5	83±5
ALHA81032	2	0.059 ±0.005	108±7	98±10
ALHA81251,8	1	0.020 ±0.002	117±4	95±19
,9	1	0.08 ±0.01	110±8	84±5
ALHA81259		0.057 ±0.005	114±4	99±5
ALHA81299		0.038 ±0.003	111±1	101±9
ALH82110		0.36 ±0.06	124±7	130±7
ALH83007,dk mtx	1	0.014 ±0.002	123±5	110±6
,lt mtx	1	0.10 ±0.03	107±4	83±5
ALH83008	2	0.059 ±0.017	117±1	96±4
ALH83010,int mtx	1	0.040 ±0.003	116±1	107±3
,lt clast	1	0.005 ±0.002	144±7	149±18
ALH83038	2	1.2 ±0.6	175±2	142±2
ALH84086	2	1.15 ±0.08	180±4	168±5
ALH84120	1	1.15 ±0.08	167±8	149±5
ALH84126	1	0.076 ±0.004	123±5	122±4
ALH84205	1	2.4 ±0.5	178±3	148±1
ALH85045	2	1.30 ±0.08	173±11	151±5
ALH85062	2	8.7 ±1.8	159±4	133±3
ALH85070	2	0.23 ±0.04	118±4	109±1
ALH85121	1	0.31 ±0.01	145±7	151±4
ALH85151	1	0.35 ±0.08	172±5	125±6
ALH85155	2	0.29 ±0.08	118±7	109±8
Bishunpur	1	0.005 ±0.003		
Bremervörde	1	0.60 ±0.2	—	—
	1	2.6 ±1.2	—	—
Brownfield (1937)	1	0.48	147	129
Carlisle Lake	1	0.46 ±0.11	149±11	149±8
Ceniceros	2	0.56 ±0.08	155±4	152±10
Chainpur	2	0.07 ±0.01	83±8	79±9
Clovis	1	0.29 ±0.01	123	150
Dhajala	1	1.0	119±6	152±8
Dimmitt	2	0.11 ±0.01	161±16	131±8
EET82601,9	1	0.9 ±0.1	164±2	114±2
,5	1	0.13 ±0.02	164±9	159±1
EET83213	1	0.57 ±0.05	162±8	156±1
EET83248	2	0.12 ±0.02	144±5	152±5
EET83260	1	0.031 ±0.002	149±2	144±5

TABLE 1. (continued).

Meteorite†	No. Splits	TL Sens. (Dhajala=1)‡	Peak Temp. (°C)‡	Peak Width (°C)‡	Meteorite†	No. Splits	TL Sens. (Dhajala=1)‡	Peak Temp. (°C)‡	Peak Width (°C)‡
EET83267	1	0.28 ±0.02	155±5	156±2	B (matrix)	1	0.091 ±0.008	168±6	144±2
EET83274	2	0.12 ±0.03	162±10	141±5	C (inclusion)	1	0.075 ±0.022	146±1	121±2
EET83395	2	0.011 ±0.005	104±2	84±7	D (inclusion)	1	0.0013±0.0003	176±27	176±21
EET83399	2	0.041 ±0.006	138±8	139±7	Moorabie	2	0.19 ±0.05	156±4	160±4
Frenchman Bay	2	0.11 ±0.03	174±13	146±14	Ngawi	2	0.25 ±0.13		
Grady (1937)	2	0.31 ±0.02	170±5	131±2	OTTA80301	2	0.52	132	162
Gunlock	1	0.014 ±0.002	169±8	160±20	Parnallee	2	0.4 ±0.2	92±5	121±12
Hedjaz	1	0.82	151	148	PCA82520	2	0.4 ±0.2	164±5	153±2
Inman	1	0.031	130	140	Prairie Dog Creek	1	0.55	123	140
Julesburg	2	0.26 ±0.02	151±4	123±5	Quinyambie	3	0.06 ±0.02	192±16	171±9
Kakangari	2	0.16 ±0.01	162±3	167±7	Ragland	1	0.07 ±0.01	116±6	101±14
Khohar	2	0.44	151	151	RKP86700	2	0.005 ±0.002	173±25	223±37
Krymka	2	0.0030±0.0002	129±14	162±28	RKPA79008	2	0.89	146	141
LEW85396	1	0.073 ±0.002	113±1	103±3	RKPA80207	2	0.013	121	104
LEW85401	1	0.024 ±0.005	105±4	72±6	RKPA80205	2	0.55	137	160
LEW86018	2	0.005 ±0.003	128±32	124±57	RKPA80256	1	0.38	150	163
LEW86021	1	0.13 ±0.01	145±9	166±2	Semarkona	2	0.0045±0.0020		
LEW86022	2	0.017 ±0.009	134±6	118±13	Sharps	2	0.08 ±0.03	115±7	116±6
LEW86127	1	0.024 ±0.004	111±4	86±5	Starvation Lake	2	0.14 ±0.06	176±6	161±9
LEW86134	2	0.0018±0.0005	150±10	106±5	St. Mary's Co	2	0.034 ±0.008	100	28
LEW86144	1	0.012 ±0.002	125±1	158±13	St. Rose	1	0.38 ±0.07	171±6	149±3
LEW86158	2	0.03 ±0.01	102±5	79±9	Suwahib (Buwah)	1	0.25	135	153
LEW86207	2	0.010 ±0.005	122±9	100±7	Tieschitz	5	0.20 ±0.07	86	93
LEW86246	1	0.057 ±0.009	131±4	133±12	TIL82408,11	1	0.0016±0.0007	180±6	165±14
LEW86270	1	0.007 ±0.002	122±10	131±8	,13	1	0.10 ±0.03	183±12	170±4
LEW86307,4A	1	0.030 ±0.003	102±4	74±3	Villa Natamoros	2	0.45 ±0.06	150±24	151±3
,4B	1	0.11 ±0.03	97±2	68±5	Wilaroy	1	0.21	147	147
LEW86367	1	0.038 ±0.004	104±5	77±3	Y74024	1	1.2 ±0.3	160±8	174±6
LEW86505	2	0.07 ±0.03	111±3	98±6	Y74032	1	0.8 ±0.2	171±3	147±3
LEW86549	1	0.004 ±0.002	166±1	143±1	Y74138	1	1.5 ±0.3	183±2	145±1
LEW87248	2	0.05 ±0.02	145±6	150±4	Y74191	1	0.6 ±0.2	124±4	137±7
LEW87254	2	0.051 ±0.005	118±3	89±6	Y74417	1	0.26 ±0.03	118±2	102±7
Manych	2	0.07 ±0.01			Y74660	1	0.0020±0.0002	185±9	150±10
Mezö-Madaras									
A (bulk)	4	0.90 ±0.33	142	145					

*Earlier versions of data for about half these samples have previously been published by *Guimon et al.* (1985), *Hewins et al.* (1988), *Prinz et al.* (1988), *Sears et al.* (1980, 1982), *Sears and Hasan* (1987), *Sears and Weeks* (1983) and *Weisberg et al.* (1989).

†Sources as follows. ALH, EET, LEW, OTT, and RKP samples (unless otherwise noted)—Meteorite Working Group of NASA/NSF; ALHA77176, ALHA77050, Bremervörde, Suwahib (Buwah), Inman, Mezö-Madaras, Ragland—E. Scott, University of New Mexico; Bishunpur, Bremervörde, Chainpur, Dhajala, Hedjaz, Khohar, Manych, Mezö-Madaras, Ngawi, Parnallee, Semarkona, Sharps, Tieschitz—see *Sears et al.* (1980); Brownfield and Clovis—H. Suess, University of California, San Diego; Carlisle Lake, Gunlock—M. Prinz, American Museum of Natural History, New York; Ceniceros—A. Graham, British Museum (Natural History), London; Dimmitt, Grady (1937); Julesburg—G. Huss, University of Chicago; Frenchman Bay Moorabie, Quinyambie, Starvation Lake, Willaroy—B. Mason, Smithsonian Institution; St. Rose—C. Caillet, Universite Pierre et Marie Curie, Paris; Y samples—National Institute of Polar Research, Tokyo; Villa Natamoros—R. Hewins, Rutgers University.

‡Uncertainties generally refer to the standard deviation shown by 3-5 replicates, compounded in cases where more than one split was available and the TL sensitivities of the splits differed by less than a factor of 3.

ALH85155 to this list (*JSC*, 1987b). These meteorites were paired primarily because they all contain abundant inclusions of poorly graphitized carbon (*McKinley et al.*, 1981; *Scott et al.*, 1981a,b, 1988; *Brearley et al.*, 1987). Inert-gas data are consistent with the pairing for 11 individuals (*Wieler et al.*, 1985), 4 of which were included in the present study (ALHA81025 and ALHA81030-2).

Figures 1a,b show plots for the induced TL data for some of the meteorites in question. The TL sensitivities have a pronounced mode at about 0.057 with a smaller "step" at about 0.23. Fifteen of the 22 meteorites have TL sensitivities within 2σ of 0.057 and cluster reasonably tightly on the TL peak temperature-width plot (Fig. 1b). The data are therefore consistent with pairing for ALHA77167, 77214, 77249, 78038, 78041, 78162, 78176, 78180, 78235, 78239, 81030-2, 81259, and 81299. Another group having TL sensitivities near 0.23 (ALHA77011, 77015, 77050, 77260, and 85155), but showing a factor of 4 spread, cluster tightly on Fig. 1b. The TL evidence for pairing of these five meteorites is less compelling than the petrographic evidence. In terms of pairing, the ^{26}Al data are

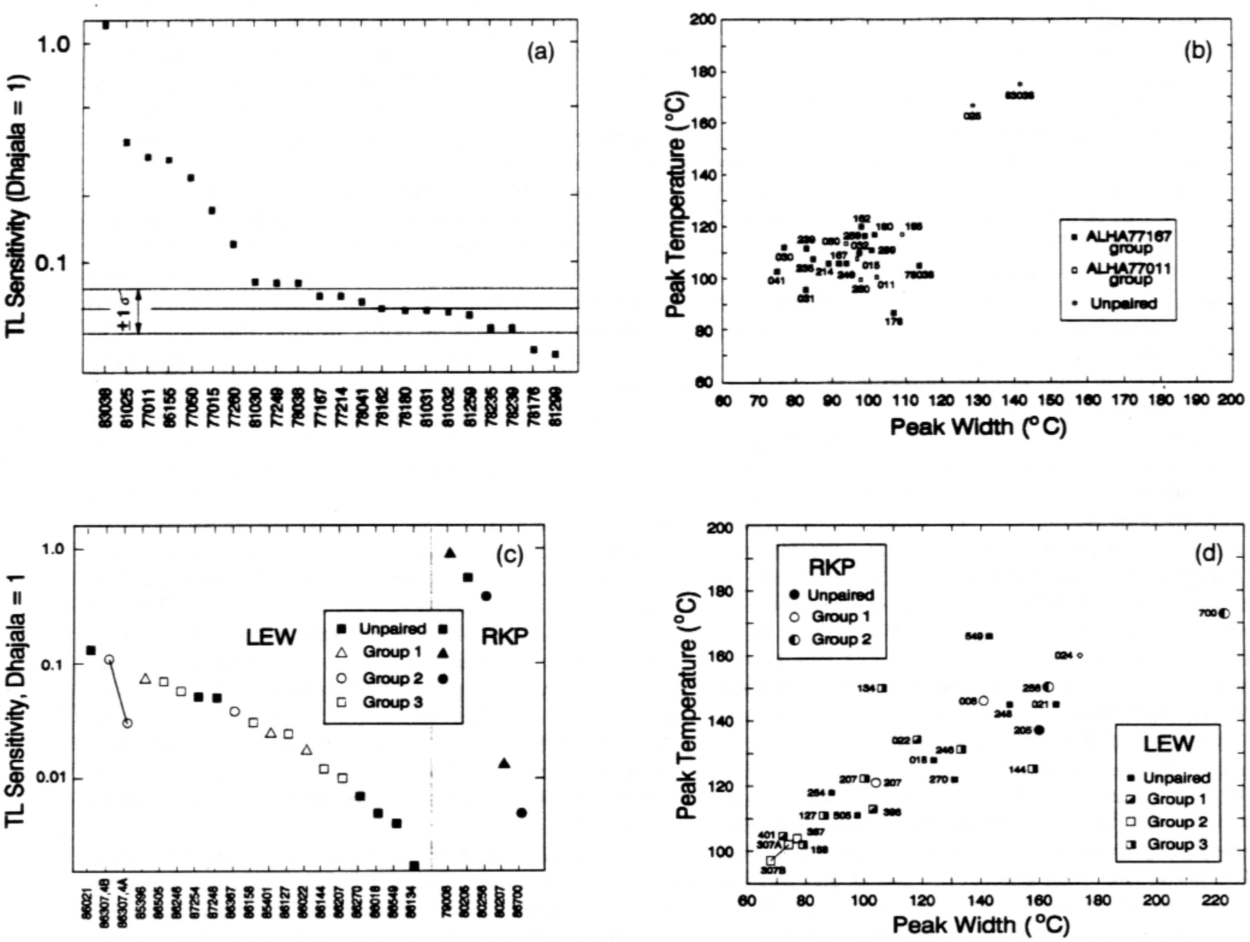


Fig. 1. **(a)** TL sensitivities of 22 type 3 chondrites from the Allan Hills paired by *Scott* (1989) and Mason (*JSC*, 1987b). The horizontal lines indicate the mean ±1σ for meteorites 81030 through 81299. **(b)** TL peak temperature against peak width for the same 22 type 3 ordinary chondrites. The ALHA77011 group (77011, 77015, 77050, 77260, and 85155) plot in a tight cluster in the middle of the field occupied by 12 other type 3 ordinary chondrites (the "ALHA77167 group"). ALHA81025 and ALH83038 plot well away from the others and are probably not paired with each other or the other type 3 ordinary chondrites plotted. **(c)** TL sensitivities of 18 type 3 chondrites from Lewis Cliff and of 5 type 3 chondrites from Reckling Peak. Lewis Cliff groups 1, 2, and 3 are the 85396, 86307, and 86127 pairing groups of Mason (*JSC*, 1987a, 1988a, 1988b), respectively, while Reckling Peak groups 1 and 2 refer to the 79008 pairing group of *Score et al.* (1982, 1984) and the 80256 pairing group of Mason (*JSC*, 1988a), respectively. **(d)** TL peak temperature against peak width for the 23 Reckling Peak and Lewis Cliff type 3 chondrites. The induced TL data do not support pairing of Lewis Cliff type 3 chondrites in a few well-defined groups like those of Allan Hills. Splits from a single meteorite are connected with tie lines.

ambiguous. On the one hand, both the ALHA77011 and ALHA77167 groups have a mode at 35-40 dpm/kg, somewhat lower than most Antarctic meteorites (40-65 dpm/kg). On the other hand, the ALHA77167 group shows more scatter in ^{26}Al than the ALHA77011 group. Also, low-^{26}Al activities may be a characteristic property of Antarctic type 3 ordinary chondrites. For instance, the ALHA77215 group, which is not paired with ALHA77011, also has ^{26}Al activities of 36-42 dpm/kg. A factor of 4 difference in TL sensitivity between splits from a single meteorite is rare. Below we assume that when it occurs it is due to brecciation, but in the present case this would be inconsistent with the uniformity of the TL sensitivity of the ALHA77167 group. We will consider these groups as two discrete meteorites, ALHA77011 and ALHA77167. On the basis of TL sensitivity and peak shape, it seems doubtful that ALHA81025 (L3.6) and ALH83038 (L3.8) are paired with either of these groups.

Scott (1984b) suggested that ALHA76004 and 81251 were paired LL3.3 chondrites and we find that they have very similar TL data. While *Wieler et al.'s* (1985) inert-gas data are consistent with pairing, *Scott* (1989) remarks on their unusually different degree of weathering (categories A and B/C respectively; *JSC*, 1986a), *Evans et al.* (1990) report that their ^{26}Al activities are significantly different (58 ± 6 and 45 ± 2 dpm/kg), and *Sears and Weeks* (1986) found that while 76004 was an L chondrite, 81251 was an H chondrite. Pairing of these two samples is therefore extremely unlikely.

Lewis Cliff. On the basis of their petrographic properties, B. Mason has suggested that there are several pairing groups among the Lewis Cliff L3 chondrites (*JSC*, 1987a, 1988a,b). Figures 1c,d show the induced TL data for some of these meteorites, with the pairings suggested by Mason indicated. Thermoluminescence sensitivities for these samples cover almost a 100-fold range, and the spread is approximately uniform except, perhaps, for a small hiatus between the sample with the lowest value, LEW86134, and its closest neighbor, LEW86549. Peak temperature and peak width data also show much scatter. These data contrast with those of Figs. 1a,b in not showing "preferred values," and any pairings present are not readily apparent. That is not say that there are no pairings; the two splits from LEW86307 differ by a factor of about 4, so the data are not inconsistent with the pairing of LEW86307 with LEW86367. There are other instances of samples with very similar TL data. However, we do find it remarkable that so many type 3.0-3.2 ordinary chondrites came from the Lewis Cliff. It is possible that these samples are paired, and that the meteorite is unusually heterogeneous due to aqueous alteration, brecciation, or some other effect. Whatever the case, on the strength of existing data, we suggest that the preferable course is to not pair any of these samples.

Reckling Peak. Data for our Reckling Peak samples are also plotted in Figs. 1c,d. RKPA86700 was paired with 80256 by B. Mason (*JSC*, 1988a). Mason found that 86700 was type 3.9, and that 80256 was type 3.9 or 4. Thermoluminescence sensitivities suggest type 3.1 for 86700 and type 3.6 for 80256. *Wieler et al.* (1985) did not find RKPA80256 to be gas-rich and therefore not paired with RKPA79008 and 80207. For our present purposes, we will not consider these as paired. RKPA79008 and 80207 were described as paired L3 chondrites by *Score et al.* (1982, 1984), and *Weiler et al.* (1985) found solar-wind gases in both. *Scott* (1984a) suggested these were not paired because his olivine compositions for 80207 corresponded to H3.6 classification; bulk analysis suggests that both meteorites are L chondrites (*Sears and Weeks*, 1986). 79008 has olivine compositions and TL sensitivity of type 3.7/3.8, while 80207 has olivine compositions and carbon contents of type 3.7/3.5 and TL sensitivity of type 3.2.

It is curious that RKPA79008/80207 and RKPA86700/80256 should both show such large disagreement between samples that are petrologically similar. On the basis of TL data, we would not be inclined to pair either duo; however, the solar gases are persuasive in the case of 79008 and 80207. Regolith breccias contain a great variety of material, including heavily shocked material and non-gas-rich clasts, so it is possible that the various, sometimes conflicting, data for some groups of potentially paired meteorites are a result of these samples being pieces of the same complex breccia. It may never be possible to be certain.

South Australia. Moorabie, Starvation Lake, and Quinyambie are unequilibrated ordinary chondrites found in the same general vicinity of the New South Wales/South Australia border region (*Clarke*, 1975; *Graham*, 1985; *Graham et al.*, 1985). Petrographic, compositional, isotopic, and TL data for these meteorites were recently described by *Sears et al.* (1990). The closeness of the findsites, petrographic type, bulk composition, oxygen isotope composition, and natural and induced TL properties suggest that all three are pieces of the same meteorite. However, there are differences, especially for Moorabie, which contains unusually reduced silicates (like those of Willaroy, *Scott et al.*, 1985a), slightly higher metal contents, and lower natural TL level. Starvation Lake is a fragmental breccia whose matrix is LL4 material of *Dodd and Jarosewich* (1979) shock facies d-e, unlike the others (E. R. D. Scott, personal communication, 1984). For all three meteorites the petrographic type determined from induced TL is lower than that determined from olivine heterogeneity, and shock would be a reasonable explanation for this; shock of facies d-f causes a ≥10 fold decrease in TL sensitivity (*Sears et al.*, 1984a). We think that there is sufficient uncertainty that these three meteorites should be considered separate falls; however, the possibility that they are paired shocked breccias should be borne in mind.

Brecciation. We have attempted to locate brecciated meteorites using four approaches: (1) We have used the *Schultz and Kruse* (1989) database for light noble gases and other data to identify gas-rich meteorites; (2) we have located petrographic descriptions of several breccias that are not gas-rich; (3) we have identified meteorites that show disagreement between splits by a factor of >2; and (4) we have identified samples that show a disagreement of >0.2 in the petrographic type determined from TL sensitivity and that determined by silicate heterogeneity (see below). The meteorites identified in these ways are listed in Table 2, with references where applicable, and will be briefly discussed below.

Five of the present samples are gas-rich breccias, and a sixth has light-dark structure typical of such meteorites. There is petrographic evidence for five of the present samples being

TABLE 2. Type 3 ordinary chondrite breccias and possible breccias in the present study.

1. *Gas-Rich Breccias*	
Ngawi	*Schultz and Kruse* (1989), *Fodor and Keil* (1975)
ALHA77216*	*Score et al.* (1981), *Score* (1980), *Nautiyal et al,* (1982), *Vogt et al.* (1986)
RKPA79008	*Wieler et al.* (1985)
RKPA80207†	*Wieler et al.* (1985)
Bremervörde*	*Binns* (1968), *Schultz and Kruse* (1989)
Dimmitt	*Rubin et al.* (1983), *Schultz and Kruse* (1989)
2. *Suspected Gas-Rich Breccias*	
ALH 83007	C. Satterwhite, personal communication, 1986; *JSC* (1986a)
3. *Non-Gas-Rich Breccias*	
ALHA76004‡	*Olsen et al.* (1978)
ALHA81251‡	*Scott* (1984b)
Mezö-Madaras‡	*Binns* (1968), *Van Schmus* (1967)
ALH 83010‡	R. Martinez, personal communication, 1985
Starvation Lake§	E. R. D.Scott, personal communication, 1984
4. *TL Chips Differ by a Factor of >3 in TL Sensitivity*	
ALHA76004‡	Bremervörde*
ALHA77216*	EET 82601
ALHA81251‡	LEW 86307
ALH 83007	Mezö-Madaras‡
ALH 83010‡	TIL 842408
5. *Petrographic Type Determined from TL Sensitivity Differs by <0.2 from Petrographic Type Determined by Silicate Heterogeneity*	
ALHA77304	Inman
ALHA79022	LEW 86021
ALH 83008	LEW 86022
ALH 85062	LEW 86549
Clovis	Moorabie§
EET 83260	RKPA80207†
EET 83395	RKPA80256
EET 83399	RkPA86700
	Starvation Lake§

*Appears in both lists 1 and 4.
†Appears in both lists 1 and 5.
‡Appears in both lists 3 and 4.
§Moorabie, Starvation Lake, and Quinyambie were found within 50 km of each other and may be paired.

brecciated, but apparently not gas-rich. Out of the 77 cases for which we ran duplicate chips, 11 cases showed disagreement between splits of a factor of >3, and there are 17 cases (out of a possible 86) where the disagreement in the equivalent petrographic type determined by TL sensitivity and that determined from olivine composition was ≥0.2. The number of instances in which meteorites appear in more than one list in Table 2 is noteworthy, especially since many of the present samples are little studied, and we infer that brecciation is the major cause of disagreement in TL sensitivity data for splits from the same meteorite, and of the disagreements in petrographic type assignment based on TL and olivine data. However, it should be stressed that in general the agreement between splits is very good and brecciation involving material of very different petrographic type is relatively rare. The number of instances where the petrographic type of splits from a single meteorite differs by more than 0.4 is exceedingly rare; only four cases are present (ALH85062, LEW86549, RKPA80207, and RKP86700).

Gas-rich meteorites. *Schultz and Kruse's* (1989) inert gas data show that Ngawi is gas-rich, and pronounced brecciation is strongly evident in its cathodoluminescence petrography. In the section shown in Fig. 2, two type 3.1 clasts are surrounded by a brecciated host material of mean type 3.6 (see also *Sears et al.,* 1989). The host material contains fragments with intense light-blue luminescence, characteristic of petrographic type 5 or 6, and individual chondrules with red grains embeddded in a mesostasis with yellow CL. The presence of chondrules whose mesostasis produces yellow CL illustrates the lack of even the mildest levels of postbrecciation metamorphism. While such chondrules are abundant in Semarkona (type 3.0), they are relatively rare in Krymka (type 3.1) and completely absent in higher types. The mixture in the host matrix of materials with such diverse CL colors, many of which are unstable to mild levels of metamorphism, is evidence for an origin for the dark matrix of regolith breccias by comminution of clasts (*DeHart and Sears,* 1988). *Fodor and Keil* (1975) describe lithic clasts in Ngawi that

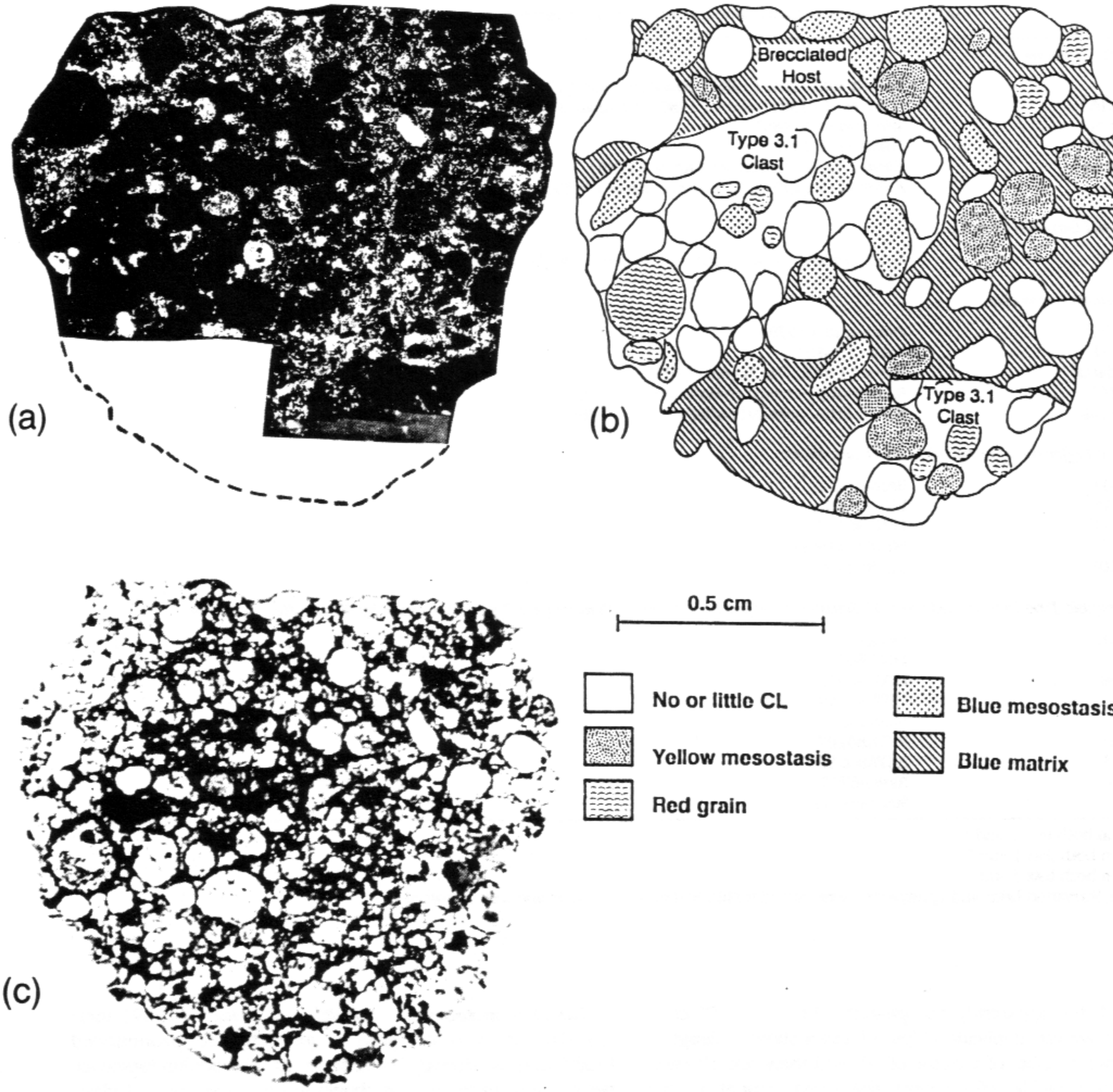


Fig. 2. **(a)** Photograph of the cathodoluminescence (CL) of the Ngawi type 3 ordinary chondrite. A colored version of this photograph appears in *Sears et al.* (1989). **(b)** Sketch of **(a)** showing the CL colors. This section shows the considerable brecciation of Ngawi and the unique ability of CL to readily distinguish petrographic types and brecciation. Two clasts of type 3.1 material, with CL properties similar to Bishunpur and Krymka (both type 3.1; see *Sears et al.,* 1989) are enclosed in a host that is a mixture of material with bright blue CL, due to sodic feldspar and characteristic of higher petrographic types, and chondrules with red grains located in a yellow mesostasis. Such chondrules are characteristic of Semarkona (type 3.0) and are rare or absent in higher petrographic types. **(c)** The same section by transmitted light.

were produced by impact working of the regolith. *Afiattalab and Wasson* (1980) found that while metal compositions often resembled those of Bishunpur (type 3.1), the processes responsible for the metal were highly "diverse."

Score et al. (1981) refer to light clasts in a darker matrix in ALHA77216 and to ALHA77252, which is paired with ALHA77216, being an "L3 chondrite with L6 clasts," while *Nautiyal et al.* (1982) report solar-flare tracks and trapped solar gases in ALHA77216. The observation of trapped solar gases in ALH77216 has been confirmed by *Vogt et al.* (1986). Our samples included a light clast and a "bulk" sample. Assuming the "bulk" sample was predominantly matrix, the relative TL sensitivities of these components suggests a fairly mature regolith, comparable with Weston and Fayetteville (*Haq et al.,* 1989).

In contrast to ALHA77216, our two splits of Dimmitt had very similar TL sensitivity and this meteorite lies on the gas-poor extreme of the range of gas contents observed for gas-rich chondrites (*Schultz and Kruse,* 1989). Both kinds of data suggest a relatively immature regolith (*Haq et al.,* 1989). The meteorite has been described in detail by *Rubin et al.* (1983).

Sears and Weeks (1983) discussed the brecciated character of RKPA79008 and Bremervörde, and subsequently *Wieler et al.* (1985) found that RKPA79008 and RKPA80207 were gas-rich regolith breccias. The brecciated character of Bremervörde has been discussed by *Binns* (1968), and *Schultz and Kruse* (1989) list "dark" samples of Bremervörde with very high contents of trapped gases.

We suspect that ALH83007 is also gas-rich. It seemed to show a light-dark structure in hand-specimen (C. Satterwhite, personal communication, 1986; see also *JSC,* 1986a) and TL measurements were made on both a sample of dark matrix and light clast. The relative TL sensitivities of the two components are indicative of an extremely mature regolith, comparable to that of Fayetteville and Leighton (*Haq et al.,* 1989).

Non-gas-rich breccias. The highly brecciated character of ALHA76004 was described by *Olsen et al.* (1978), who also observed that its texture was similar to that of Ngawi and Mezö-Madaras. ALHA81251 is petrographically so similar that it was thought to be paired with ALHA76004 (*Scott,* 1984b). Mezö-Madaras was described by *Binns* (1968) and *Van Schmus* (1967). Clasts of equilibrated, unequilibrated, shocked, and carbonaceous material are present, but the trapped gases in the clasts measured to date appear to be normal (i.e., ^{20}Ne contents are $9.8\text{-}13.1 \times 10^{-8}$ cc STP/g; *Schultz and Kruse,* 1989), suggesting that it is not a regolith breccia. Petrographic examination was performed on three of the present samples by E. Scott. A sample of host matrix had a TL sensitivity corresponding to type 3.4, compared with the bulk value of 3.7. This reflects the presence of equilibrated clast material in the bulk samples. Two inclusions had TL sensitivities corresponding to type 3.4 and 3.0, although the latter inclusion is heavily shocked and its low TL sensitivity is undoubtedly a reflection of this. The petrographic properties of the other inclusion were consistent with its petrographic type assignments. The carbon content of Mezö-Madaras varies considerably from sample to sample (0.193-0.46 w/w%, *Moore and Lewis,* 1967; *Grady et al.,* 1989), presumably reflecting the diversity of petrographic types present.

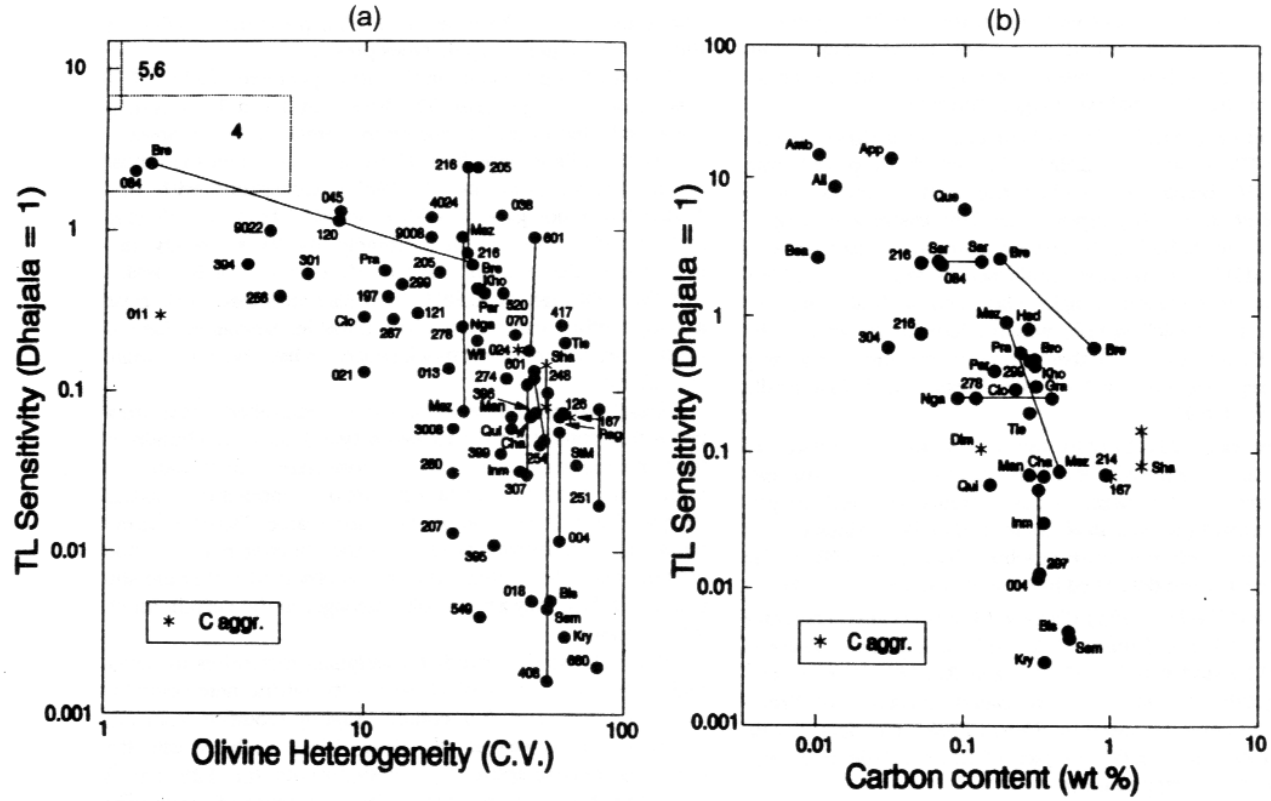
The only feature visible on the hand-specimen of ALH83010 was an isolated light clast. The light clast has a TL sensitivity one-eighth that of an interior sample, unlike regolith breccias in which the light clasts have TL sensitivities higher than those of the matrix (*Haq et al.,* 1989). Consistent with this, ALH83010 is not gas-rich (*Wieler et al.,* 1985). A melt clast in Fayetteville also had an extremely low TL sensitivity, due to fusion of the feldspar (*Haq et al.,* 1989), so it is possible that the light clast in ALH83010 is also an impact melt clast, although other explanations are possible. Starvation Lake is another breccia in which shock processes have been important (see above).

Classification. *Sears et al.* (1980) identified seven properties that could be used to assign type 3 ordinary chondrites to a petrographic type, but unfortunately only four are commonly available. Data on metal composition, matrix recrystallization, and composition are scarce. Figure 3 shows plots of TL sensitivity against olivine heterogeneity, carbon content, and ^{36}Ar content. The trends observed earlier are still present; in fact, they are probably stronger in the current much larger dataset.

Table 3 shows the criteria for assigning meteorites to petrologic type on the basis of TL sensitivity, olivine heterogeneity, carbon content, and ^{36}Ar content, slightly modified from our earlier papers (*Sears et al.,* 1980, 1982). Table 4 lists the resulting petrographic type assignments for 125 type 3 chondrites for which we have TL data. Because of weathering (see below) and sample heterogeneity, all petrographic type assignments are thought to carry an uncertainty of about 0.1. We have also indicated in Table 4 those samples that we believe are breccias, those that are known to be gas-rich regolith breccias, and those that *Anders and Zadnik* (1985) found to be rich in volatile elements, but are not known to be breccias. We stress that the interpretation of a petrographic type for breccias, especially regolith breccias whose matrix is a mixture, must be made with caution.

Zinner (1988) recently suggested that Krymka was petrographic type 3.7 on the basis of deuterium data of *McNaughton et al.* (1982). The induced TL data indicate type 3.1, as does cathodoluminescence petrography (*Sears et al.,* 1989). Zinner was apparently unaware of deuterium data reported by *Devirts et al.* (1985) that show deuterium enrichments relative to SMOW of 4000-5000‰, consistent with a petrographic type of about 3.1 (*McNaughton et al.,* 1982). It might be that Krymka is brecciated, but, as *Zinner* (1988) points out, deuterium is very heterogeneously distributed in type 3 ordinary chondrites.

We have compared the present petrographic type assignments with those suggested by B. Mason in his initial descriptions for the *Antarctic Meteorite Newsletter.* In general, the agreement is very good. Of the 24 meteorites for which comparison is possible, the present classification differs significantly (by greater than 0.2) from Mason's in only three cases, ALH85062, LEW86021, and LEW86549. We also note that olivine heterogeneity is not well suited to discriminating below type 3.5 and many of Mason's type 3.5 assignments should be read as type ≤3.4 (*Sears et al.,* 1982).



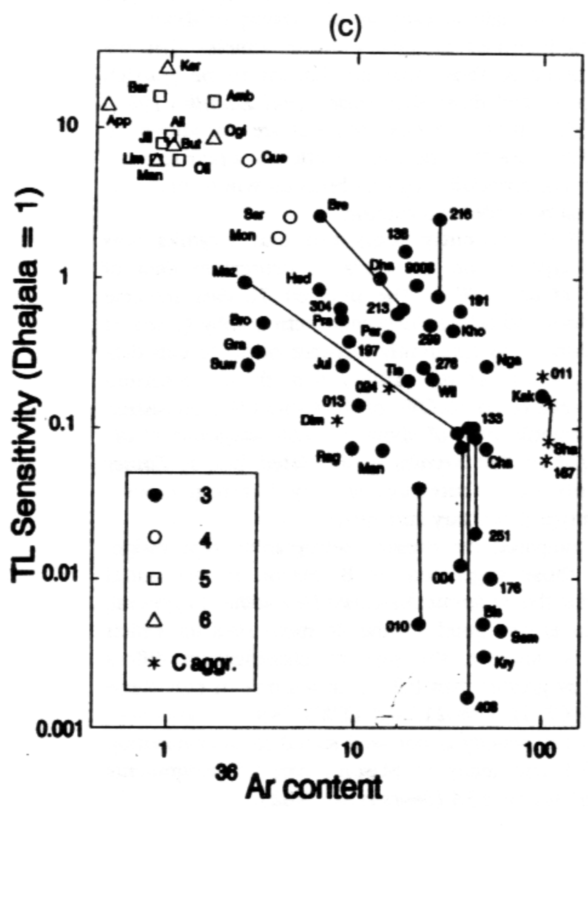


Fig. 3. TL sensitivity against **(a)** olivine heterogeneity (expressed as the standard deviation as a percentage of the mean, or coefficient of variation, C.V., see *Sears and Weeks,* 1983, or *Scott,* 1984a), **(b)** carbon content (wt%), **(c)** ^{36}Ar content ($\times 10^{-8}$ cc STP/g). The olivine data are from the appropriate issues of the *Antarctic Meteorite Newsletter* and *Meteorites News, Sears et al.* (1982, and references therein), *Sears and Weeks* (1983, and references therein), *Dodd et al.* (1967), *Noonan et al.* (1977), *Huss et al.* (1981), *McKinley and Keil* (1984), and *Recca et al.* (1986); carbon data from *Moore and Lewis* (1967) and *Grady et al.* (1982, 1989); ^{36}Ar data from *Schultz and Kruse* (1989). Meteorites may be identified from Table 1; either the last three or four numbers or the first three letters of the meteorites' names have been used. Data for meteorites that are thought to be paired (see the text) have been averaged and carbon data for ALHA77216 are for the paired sample ALHA77215. The asterisks refer to meteorites known to contain unusual carbonaceous aggregates. With the exception of the meteorites containing C-rich inclusions, TL sensitivity decreases with increasing olivine heterogeneity, carbon, and ^{36}Ar contents in the manner observed by *Sears et al.* (1980) for 13 type 3 chondrite falls.

TABLE 3. Definitions of petrologic type in terms of TL sensitivity.*

Pet. Type	TL Sens. (Dhajala=1)	C.V.† (%)	^{36}Ar (10^{-8} cm^3 STP g^{-1})	C (wt%)
3.0	<0.0046	*>50*	≥65	≥0.60
3.1	0.0046-0.010	*>50*	55-65	0.50-0.60
3.2	0.010 -0.022	*>50*	45-55	0.43-0.50
3.3	0.022 -0.046	*>50*	35-45	0.38-0.43
3.4	0.046 -0.100	*>50*	27-35	0.30-0.33
3.5	0.100 -0.22	40-50	18-27	0.33-0.30
3.6	0.22 -0.46	30-40	13-18	0.27-0.30
3.7	0.46 -1.0	20-30	8-13	0.24-0.27
3.8	1.0 -2.2	10-20	4-8	0.21-0.24
3.9	2.2 -4.6	5-10	<4	≤0.21

* *Sears et al.* (1980; 1982) with minor modification (italics).

†Coefficient of variation (σ as a percentage of the mean) of the fayalite in the olivine. (C.V. ≈ P.M.D./0.80; *Sears and Weeks,* 1983; *Scott,* 1984a.)

Weathering

Sears et al. (1982) found that acid-washing three Antarctic type 3 chondrites, which were brown in color and belonged to weathering category C, caused a restoration of their fresh gray appearance and an increase in TL sensitivity by a factor of 3. They therefore added 0.1 to the petrographic type assignments for Antarctic meteorites. Weathering is almost certainly affecting our data, although the effects are small compared with the total range of TL sensitivities observed. J. Grossman (personal communication, 1990) has found that the factor of about 2 range in the TL sensitivities for the ALHA77167 pairing group correlates with a factor almost 1000 range in mass, which might suggest that the range is due to weathering. He also finds some indication that the discrepancy between petrographic type assigned using TL data and that determined from silicate compositions is greater for meteorites of weathering category B than for weathering category A. We have tried to take the possible effect of weathering into account when comparing petrographic types derived from TL sensitivity with those obtained by the other techniques and in arriving at our recommended value in Table 4. In cases where only TL data were available, the petrographic type obtained from TL has not been changed, and it should be borne in mind that these values may be low. An assumed uncertainty of 0.1 in petrographic type should normally include any effect of weathering.

DISCUSSION

Primitive Meteorites

One of the main reasons for the subdivision of type 3 ordinary chondrites is to identify the meteorites that have suffered least metamorphic alteration and that best preserve a record of nebular processes. To date there are 12 ordinary chondrites of petrographic type 3.0-3.2 (Bishunpur, Gunlock, Krymka, LEW86018, LEW86022, LEW86134, LEW86144, LEW86158, LEW86207, LEW86270, Semarkona, and Y74660) and 10 breccias that appear to contain some material of type 3.0-3.2 (ALHA76004, ALHA81251, ALHA83007, EET83395, LEW86549, Ngawi, RKPA86700, RKPA80207, RKP86700, and TIL82408). (We exclude Mezö-Madaras inclusion D and the light clast from ALH83010 from these lists because their low TL sensitivity is thought to be due to shock-related processes.) Important among the present samples are the L3 chondrites from Lewis Cliff, since they constitute a large mass of very low petrographic type material.

Semarkona (3.0) and Bishunpur (3.1) contain hydrous silicates and calcite and have apparently experienced aqueous alteration (*Hutchison et al.,* 1987; *Alexander et al.,* 1989). Hutchison et al. suggested that it was aqueous alteration that destroyed feldspar and resulted in their low TL sensitivities. It is certainly true that the induced TL properties of type 3.0-3.2 ordinary chondrites are qualitatively and quantitatively different from those of the higher types (*Sears et al.,* 1982). *Guimon et al.* (1988) also found that under specific conditions, low temperatures and short annealing times, hydrothermal annealing lowered TL sensitivities by an order of magnitude or more. On the other hand, cathodoluminescence studies of type 3 ordinary chondrites are not consistent with aqueous alteration playing a major part in determining TL levels of these meteorites (*Sears et al.,* 1989; J. M. DeHart, G. E. Lofgren, and D. W. G. Sears, unpublished data, 1990). Nevertheless, type 3.3 ordinary chondrites assume a special significance for early solar system studies if, as suggested by *Hutchison et al.* (1987) and *Alexander et al.*(1989), aqueous alteration effects are common in type 3.0-3.2 chondrites. They are also the meteorites in which incipient metamorphism has occurred, and may in some senses provide a better reference point for studies of metamorphic effects.

In the type 3.3 category we currently have four meteorites (ALH83010, LEW85401, LEW86127, and St. Mary's County) and four breccias that apparently contain some type 3.3 material (LEW86307, EET83260, EET83399, and Inman). Inman has been described in detail by *Keil et al.* (1978), and St. Mary's County has been described by *Noonan et al.* (1977)

TABLE 4. Assignment of petrographic types using TL, olivine heterogeneity, carbon and ^{36}Ar data.

		Type							Type				
Meteorite*	Class†	TL Sens.‡	C.V.§	w/w %C¶	^{36}Ar**	Rec.††	Meteorite*	Class†	TL Sens.‡	C.V.§	w/w %C¶	^{36}Ar**	Rec.††
ALHA76004	L	3.2/3.4	≤3.4	3.5	3.3	3.2/3.4	ALH83010	L	3.1‡‡/3.3				3.3
ALHA77011	L	3.6	3.5				ALH83038	L	3.8	3.8	3.6		3.8
ALHA77015	L	3.5	≤3.4		3.0		ALH84086	LL	3.8				3.8
ALHA77050	L	3.6				3.5v	ALH84120	L	3.8	3.9			3.8
ALHA77260	LL	3.5	3.5		3.0		ALH84126	LL	3.4	<3.4			3.4
ALHA85155	L	3.6	3.7				ALH84205	L	3.9	3.7			3.9
ALHA77013	LL	3.5	3.7		3.7	3.6	ALH85045	L	3.8	3.9			3.8
ALHA77167	L	3.4	≤3.4		3.0		ALH85062	L	4	3.5			3.5/4
ALHA77214	L	3.4	<3.4	3.0	3.0		ALH85070	L	3.6	3.6			3.6
				3.0	3.0		ALH85121	H	3.6	3.8			3.7
ALHA77249	L	3.4	3.5				ALH85151	Anom	3.6				3.6
ALHA78038	L	3.4	3.5				Bishunpur	LL	3.1	≤3.4	3.1/3.2	3.2	3.1
ALHA78041	L	3.4					Bremervörde	H	3.7	3.7	3.0	3.8	(3.7/3.9)
ALHA78162	L	3.4							3.9	4	3.8	3.4	
ALHA78176	L	3.3	<3.4				Brownfield	H	3.7		3.4	3.9	3.7
ALHA78180	L	3.4				3.4v	(1937)						
ALHA78235	L	3.4					Carlisle Lake	Anom	3.7				3.7
ALHA78239	L	3.4					Ceniceros	H	3.7				3.7
ALHA81030	L	3.4			3.0		Chainpur	LL	3.6	3.5	3.2/3.5	3.4	3.4
ALHA81031	L	3.4			3.0		Clovis	H	3.6	3.9	3.8		3.6/3.9
ALHA81032	L	3.4	3.0				Dhajala	H	3.8			3.6	3.8
ALHA81299	L	3.3					Dimmitt	H	3.5		3.9	3.8	3.6
ALHA81259	L	3.4					EET82601	L	3.5/3.7	3.5			3.5/3.7
ALHA77176	LL	3.2			3.2	3.2	EET83213	L	3.7			3.6	3.7
ALHA77197	L	3.6	3.8		3.7	3.7	EET83248	H	3.5	3.5			3.5
ALHA77216	H	3.7/3.9	3.7		3.4	(3.7/3.9)	EET83260	L	3.3	3.7			3.3/3.7
ALHA77278	LL	3.6	3.7	3.9	3.5	3.7	EET83267	H	3.6	3.8			3.6
ALHA77299	H	3.7	3.8	3.4/3.6	3.5	3.7	EET83274	L	3.5	3.6			3.6
ALHA77304	L	3.7	4		3.7	3.7/4	EET83395	L	3.2	3.6			3.2/3.6
ALHA78084	H	3.9	4			4	EET83399	L	3.3	3.6			3.3/3.6
ALHA78119	L	3.5				3.5	Frenchman Bay	L	3.5				3.5
ALHA78133	L	3.5			3.3	3.5	Grady (1937)	H	3.6			3.9	3.7
ALHA78138	LL	3.5				3.5	Gunlock	L	3.2				3.2
ALHA79022	L	3.7	4			3.7/4	Hedjaz	L	3.7			3.8	3.7
ALHA81024	H	3.5	3.5		3.6	3.6	Inman	L	3.3	3.6	3.4	3.3	3.3/3.6
ALHA81025	L	3.6	≤3.4			3.6	Julesburg	L	3.6			3.7	3.6
ALHA81251	H	3.2/3.4	≤3.4		3.3	3.2/3.4	Kakangari	Anom	3.5			3.0	3.5v
ALH82110	H	3.6				3.6	Khohar	L	3.6	3.7	3.5/3.4	3.5	3.6
ALH83007	L	3.2/3.5				(3.2/3.5)	Krymka	LL	3.0	<3.4	3.6/3.6	3.2	3.1
ALH83008	L	3.4	3.7			3.4/3.7	LEW85396	L	3.4				3.6

TABLE 4. (continued).

Meteorite*	Class†	Type: TL Sens.‡	Type: C.V.§	Type: w/w %C¶	Type: ^{36}Ar**	Rec. ††
LEW85401	L	3.3				3.3
LEW86018	L	3.1	≤3.4	3.4		3.1
LEW86021	L	3.5	3.9			3.5/3.9
LEW86022	L	3.2	3.5			3.2/3.5
LEW86127	L	3.3	≤3.4			3.3
LEW86134	L	3.0	≤3.4			3.0
LEW86144	L	3.2	≤3.4			3.2
LEW86158	L	3.2	≤3.4			3.2
LEW86207	L	3.2	≤3.4			3.2
LEW86246	L	3.4	≤3.4			3.4
LEW86270	L	3.1	≤3.4			3.1
LEW86307	L	3.3/3.5	3.5			3.3/3.5
LEW86367	L	3.3	3.5			3.4
LEW86505	L	3.4	≤3.4			3.4
LEW86549	L	3.0	3.7			3.0/3.7
LEW87248	L	3.4	3.5			3/5
LEW87254	LL	3.4	3.5			3.5
Manych	LL	3.4	3.6	3.6	3.6	3.5
Mezö-Madaras	LL	3.4/3.7	3.7	3.2/3.9	3.4	3.4/3.7
		3.0‡‡/3.7		3.3		
Moorabie	L	3.5‡‡	3.8	≤3.9		3.8
Ngawi	LL	3.5	3.7	3.9	3.2	(3.2/3.7)
OTTA80301	H	3.7	3.9			3.8
Prairie Dog Creek	H	3.7	3.9	3.4	3.7	3.8
PCA82520	H	3.6	3.6			3.6

Meteorite*	Class†	Type: TL Sens.‡	Type: C.V.§	Type: w/w %C¶	Type: ^{36}Ar**	Rec. ††
Parnallee	LL	3.6	3.7	3.9	3.6	3.7
Quinyambie	LL	3.4‡‡	3.6	≥3.9/3.3		3.4/3.9
Ragland	LL	3.4	≤3.4		3.7	3.4
RKPA79008	L	3.7	3.8		3.5	(3.5/3.8)
RKPA80207	L	3.2	3.7	3.5		(3.2/3.7)
RKPA80205	H	3.7	3.8			3.8
RKPA80256	L	3.6	4			3.6/4
RKPA86700	L	3.0‡‡	3.9			3.0/3.9
Semarkona	LL	3.0	≤3.4	3.1/3.1	3.0	
Sharps	H	3.4	3.5	3.0/3.0	3.5	] 3.5
					3.5	
St. Mary's Co.	LL	3.3	≤3.4			3.3
Starvation Lake	LL	3.5‡‡	3.9	≥3.9		3.9
St. Rose	H	3.6				3.6
Suwahib (Buwah)	L	3.6		3.9	3.7	
Tieschitz	L	3.5	≤3.4	3.7/3.6	3.6	3.6
TIL82408	LL	3.1/3.5	≤3.4		3.3	3.1/3.5
Villa Natamoros	L	3.6				3.6
Wilaroy	H	3.5	3.7		3.7	3.6
Y74024	L	3.8	3.8			3.8
Y74032	H	3.7				3.7
Y74138	H	3.8			3.5	3.7
Y74191	LL	3.7			3.3	3.7
Y74417	H,L	3.6	≤3.4			3.5
Y74660	LL	3.0	≤3.4			3.0

* Paired meteorites (according to present and literature data) are indented following the first member of the pairing group.

† *NIPR* (1983), *JSC* (1986a,b, 1987a,b, 1988a,b), *Davis et al.* (1977), *Dodd et al.* (1967), *Graham et al.* (1977, 1985), *Hartmetz et al.* (1990), *Hewins et al.* (1988), *Jarosewich* (1967), *Kallemeyn et al.* (1989), *Lindstrom* (1989), *Noonan et al.* (1977), *Prinz et al.* (1988), *Rubin et al.* (1983), *Rubin and Kallemeyn* (1989), *Sears and Weeks* (1986), *Weisberg et al.* (1989), *Yanai and Kojima* (1984, 1987), B. Mason, personal communication (1984), C. Caillet, personal communication (1989), and A. Graham, personal communication (1989).

‡ Table 1.

§ *JSC* (1987b, 1988a,b), *Dodd et al.* (1967), *Huss et al.* (1981), *Lindstrom* (1989), *McKinley and Keil* (1983), *Noonan et al.* (1977), *Reca et al.* (1986), *Score* (1980), *Scott* (1984a), *Sears et al.* (1982), *Yanai and Kojima* (1984).

¶ *Fredriksson et al.* (1968), *Grady et al.* (1982, 1989), *Hartmetz et al.* (1990), *Moore and Lewis* (1967).

** *Schultz and Kruse* (1989).

†† Recommended petrologic type. Two values separated by a slash indicate a breccia, "v" indicates that the sample is "volatile-rich" (*Anders and Zadnik*, 1985). Data in parentheses are for regolith breccias and should be used with caution (see text).

‡‡ TL sensitivity probably low due to intense shock (see text).

and *Lu et al.* (1989). Brief descriptions of EET83260 and EET83399 appear in the *Antarctic Meteorite Newsletters* (*JSC*, 1986a,b, 1988a). Ironically, the only sample of type 3.3 material apparently free of terrestrial aqueous alteration weighs <20 g (St. Mary's County).

Anders and Zadnik (1985; *Zadnik*, 1985) pointed out that 5 type 3 ordinary chondrites of the 22 they considered contain higher abundances of inert gases and other volatile elements than expected on the basis of TL sensitivity and olivine heterogeneity. Since volatile-element content is as important as lack of metamorphism in identifying "primitive" meteorites, Anders and Zadnik proposed an alternative scheme of subclassification based on volatiles. The five meteorites are Sharps 3.5/0, ALHA77011 3.5/0, Ngawi 3.7/3, ALHA77299 3.7/4, and Mezö-Madaras 3.7/3, where the number following the slash is the Anders/Zadnik volatile-element subclassification.

Because TL sensitivities and inert-gas content vary over many orders of magnitude and have opposite dependencies on "primitiveness," the two phenomena respond very differently to mixing; petrographic types assigned on the basis of TL sensitivity will be much higher than those based on inert-gas contents. The discrepancies noted by *Anders and Zadnik* (1985) are therefore most probably due to the mixing of high TL "equilibrated" material with high gas-bearing "primitive" material. *Anders and Zadnik* (1985) discussed the role of mixing, but felt that the concordancy of C, inert-gas and volatile-element abundancies, and lack of petrographic evidence for gas-rich inclusions precluded the idea. We dispute this latter observation. Two of the five anomalous meteorites mentioned by *Anders and Zadnik* (1985), Ngawi and Mezö-Madaras, were among the breccias discussed above, while two of the others, ALHA77011 and Sharps, are among the many meteorites that contain unusual carbonaceous inclusions.

Inclusions once known as graphite-magnetite inclusions and subsequently referred to as poorly graphitized carbon inclusions, or simply carbon-rich aggregates, have been found in the ALHA77011 and ALHA77167 groups, Sharps (H3.4), ALHA81024 (H3.5), and Dimmitt, as well as Roosevelt County 001, Plainview, and Study Butte that were not studied here (*McKinley et al.*, 1981; *Scott et al.*, 1981a,b, 1986, 1988; *Rubin et al.*, 1983; *Brearley et al.*, 1987; *Fredriksson et al.*, 1989). Roosevelt County 001, Plainview, Dimmitt, and Study Butte are gas-rich regolith breccias, and it is worth considering whether the C-rich inclusions are always postmetamorphic additions. Several authors have suggested that the volatile-element enrichments in gas-rich meteorites were due to the addition of millimeter- to submillimeter-sized carbonaceous chondrite fragments (*Wilkening*, 1976; *Müller and Zahringer*, 1966; *Mazor and Anders*, 1967), and on occasion larger fragments are found, often dehydrated (*Wasson and Wetherill*, 1979). There are other ideas for the source of the volatile element enrichment in the dark matrix of gas-rich regolith breccias (*Rieder and Wänke*, 1969; *Dreibus and Wänke*, 1980; *Pellas*, 1972; *Bischoff et al.*, 1983), but these well-documented ubiquitous C-rich aggregates must be playing some part in the volatile-element inventory. *Scott et al.* (1988) found that three out of four of the C-rich aggregates they examined had very high concentrations of ^{36}Ar, meaning that these inclusions could account for the excess volatiles. Samples in the present study containing C-rich aggregates are indicated on Fig. 3. While these samples plot coherently on the TL sensitivity vs. olivine heterogeneity plot, at least two of them plot to higher values of C and ^{36}Ar. We suggest that this is additional evidence that the aggregates were postmetamorphic additions. *Anders and Zadnik* (1985) are correct that the higher-than-expected volatile-element contents of certain type 3 chondrites indicate that they are, in a sense, more primitive, but the "primitive" material is this late addition and not the meteorite as a whole.

Paleothermometry

In addition to allowing an assessment of relative metamorphic intensity, induced TL data provide some indication of metamorphic temperatures. Based on data for 9 observed falls and 14 Antarctic meteorites, *Guimon et al.* (1984, 1985) found that type 3.2-3.5 chondrites plotted in a different field from the type 3.6-3.9 chondrites on a plot of TL peak temperature against TL peak width. The type 3.2-3.5 chondrites have narrower peaks at lower glow-curve temperatures than the higher types. *Guimon et al.* (1984, 1985) also found that laboratory annealing of a type 3.4 chondrite caused the TL peak shape to change in a way that moved the data from the "low" cluster to the "high" cluster. Their data are reproduced in Fig. 4. The annealing data do not overlap precisely with the data in Fig. 5, most probably because of the inadequacy of our efforts at correcting for temperature lag in the annealing data. However, despite this these data show conclusively that the upper limit for the metamorphism of type ≤3.5 chondrites is 800°C.

Figure 5 is a plot of TL peak temperature against TL peak width for the present data. With a database four times that previously available, the type 3 ordinary chondrites still plot in two fields with lower petrologic type 3.2-3.4 predominantly in

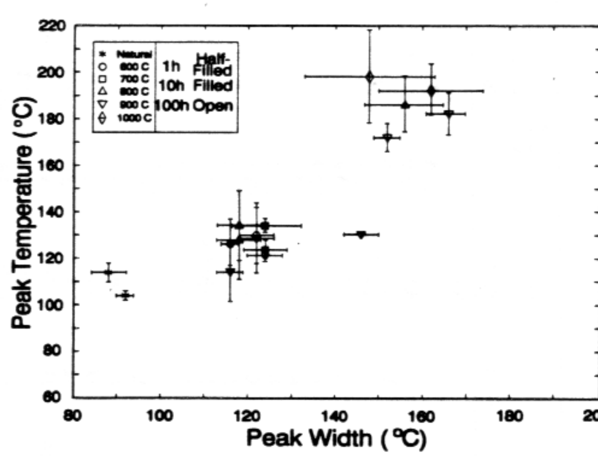


Fig. 4. Plot of peak temperature against peak width for samples of ALHA77214 annealed at a variety of temperatures for the times indicated. Data from *Guimon et al.* (1985), corrected for temperature lag in the TL apparatus. These data may be compared with the peak temperature and peak width for type 3 ordinary chondrites in Fig. 5.

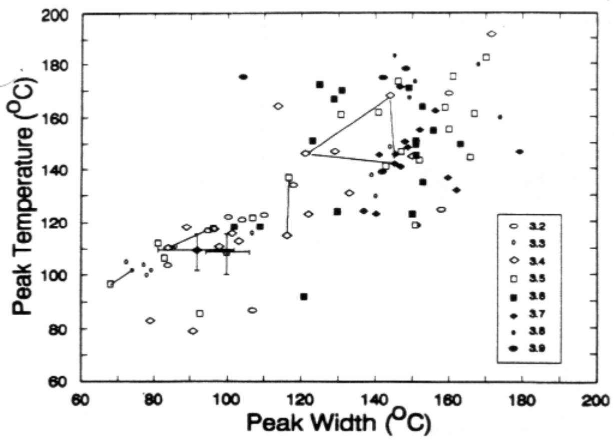


Fig. 5. Plot of TL peak temperature against peak width for type 3 ordinary chondrites in the present study. The petrologic type indicated by TL sensitivity is indicated; this is normally, but not always, the same as the "recommended" type in Table 4. Splits from a single meteorite are connected with tie-lines. The data plot in two clusters, one containing type 3.2-3.4 chondrites and another containing type 3.6-3.9 chondrites, with type 3.5 chondrites straddling the two clusters.

the lower field and type 3.6-3.9 predominantly in the upper. In the new database, type 3.5 plot in both fields. The separation of petrologic types in this way is an indication that the TL peak shape data also contain information on the thermal history.

There are reasonable grounds for thinking that the mechanism behind the peak shape change involves the ordering of the feldspar; most probably, the feldspar is ordered in type ≤3.5 and at least partially disordered in type ≥3.5. Several terrestrial feldspars in the low form have peaks around 100°C (*Batchelor and Sears,* 1989), while artificially disordered terrestrial feldspars, and feldspar in equilibrated chondrites (which is known to be fairly disordered; *Van Schmus and Ribbe,* 1968), have peak temperatures of ~200°C. If this interpretation is correct, then the type 3.5 corresponds to the order/disorder transformation temperature (probably 500°-600°C). The feldspar system is, of course, compositionally and structurally very complicated. Furthermore, the details of the disordering process itself are incompletely understood. It is therefore very striking that feldspars from a wide variety of sources, terrestrial and extraterrestrial, behave so similarly with respect to their TL properties, including their response to annealing (*Guimon et al.,* 1985; *Hasan et al.,* 1986; *Keck and Sears,* 1987; *Hartmetz and Sears,* 1987; *Batchelor and Sears,* 1990).

Metamorphic temperatures of 500°-600°C for type 3.5 are in reasonable agreement with the small amount of other available data. The presence of correlations between central Ni content and diameter for taenite grains in Tieschitz (type 3.6), Chainpur (type 3.4), and Mezö-Madaras (type 3.4/3.7) suggested that they had been heated to at least 500°C, which was not true of Bishunpur and Krymka (both type 3.1), whose central Ni content was consistent with equilibration at about 400°C (*Wood,* 1967; *Dodd,* 1969, 1981). Using Ni content of kamacite, *Rambaldi and Wasson* (1981) proposed metamorphic temperatures of 300°-350°C for Bishunpur with "the record of higher temperatures" in other grains, and they found that the Ni contents of phosphides corresponded to equilibration temperatures of around 400°C. The Cr-spinel/olivine thermometer of *Roeder et al.* (1979) and *Fabriès* (1979) yields temperatures of 600°-700°C for three type H3.6-3.8 chondrites (Dhajala, H3.8; Study Butte, H3.6; Clovis #1, H3.6) (*Wlotzka,* 1985, 1987), but Tieschitz (type 3.6) and Sharps (type 3.5) were too unequilibrated for the method. *Brearley* (1990) has applied *Rietmeijer and Mackinnon's* (1985) thermometer, based on lattice spacing in graphitic material that decreases with graphitization, and found 300°-450°C for Sharps (type 3.5), ALHA77167 (type 3.4), ALHA77011 (type 3.5), ALHA81024 (type 3.6), Dimmitt clast DT1 (type 3.6), and Plainview clast PV1 (gas-rich regolith breccia). The temperature estimates based on graphitization are about 100°C lower than the other temperature estimates, but this thermometer is poorly calibrated (e.g., the choice of an empirical calibration plot apparently involves assumptions about the duration of metamorphism) and applies only to the C-rich aggregate clasts, which may have been placed in the meteorite after metamorphism of the host. *Dodd* (1969, 1981) suggested that the upper limit for the metamorphic temperature of type 3 ordinary chondrites is 600°C, the temperature at which low-Ca clinopyroxene converts to low-Ca orthopyroxene. Pyroxene equilibria and O-isotope distributions have been successfully applied to paleothermometry for the higher petrologic types, but fail with the unequilibrated chondrites (*McSween and Patchen,* 1989; *Onuma et al.,* 1972).

Class Differences in Petrographic Type

Figure 6 shows histograms of TL sensitivities for the present samples, with the meteorites divided according to chemical class; classifications are taken from the sources listed in Table 3. The classification of type 3 chondrites, especially distinguishing L from LL chondrites, is not straightforward (*Sears and Weeks,* 1986). This is because the criteria best suited to the purpose are those involving oxidation state (Fa in olivine and Co in kamacite) and type 3 chondrites are reduced by various amounts relative to equilibrated chondrites. Also, their O isotopes do not plot in the fields of the equilibrated ordinary chondrites. Classification therefore tends to rely on bulk composition or amount of metal, but while the equilibrated H chondrites are well resolved compositionally, the equilibrated L and LL chondrites grade into each other. Notwithstanding these classificational difficulties, it is clear that H chondrites tend toward higher TL sensitivity and higher petrographic types, while L and LL chondrites show lower, approximately normal distribution; aside from two splits of ALHA81251, H chondrites have petrologic type >3.4.

We can suggest three explanations (or partial explanations) for the difference in petrographic type distributions shown by the H and other type 3 chondrites. (1) The available heat source was ^{26}Al, and the H chondrite parent body formed before the other parent bodies at a time when the nuclide was more abundant. (2) The ordinary chondrite parent bodies were internally heated by radioactive decay, so that the bodies

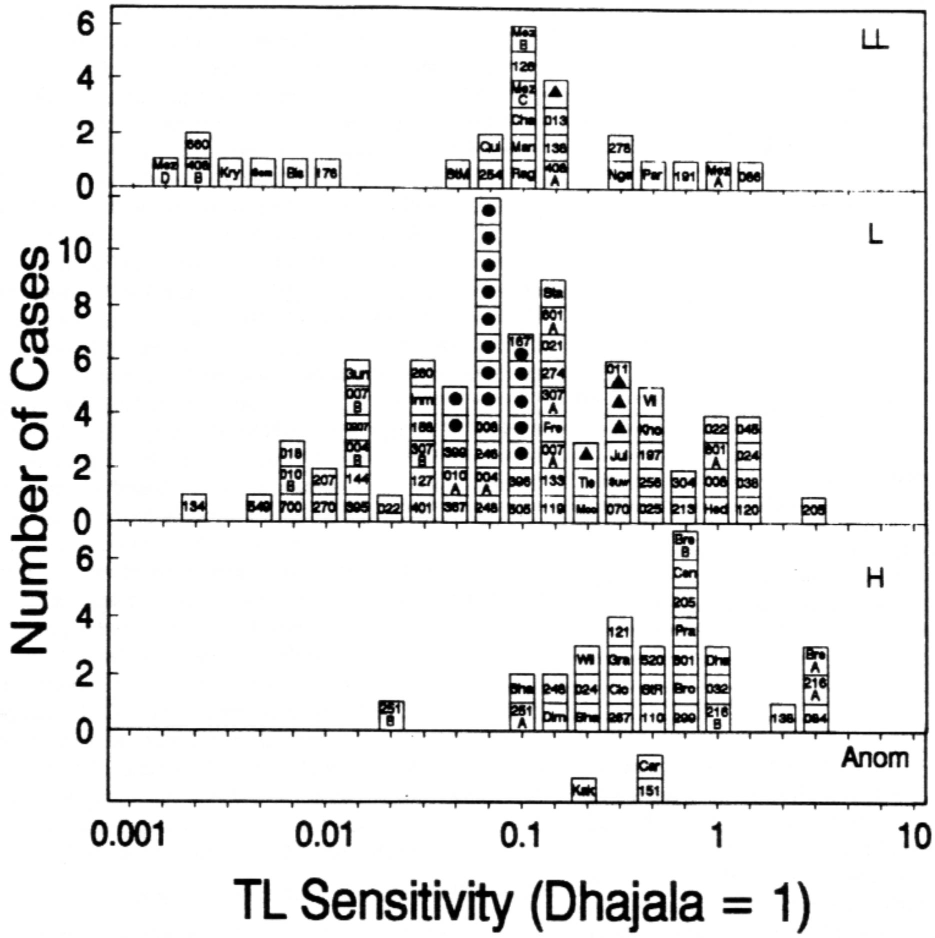


Fig. 6. Histograms of TL sensitivity for type 3 ordinary chondrites by H, L, and LL class. Circles and triangles represent the ALHA77167 and ALHA77011 pairing groups, respectively. There is a marked tendency for the TL sensitivity to skew to higher values for the H class. Meteorites of uncertain classification in Table 3 have been omitted, as is ALH85062, which is petrographic type 4.

had a simple spherically symmetrical temperature gradient with the highest temperatures at the center, and the H chondrites came from greater burial depths than the other classes. (3) Differences in physical properties between the H chondrites and the other classes are the crucial factor in determining thermal history. This would be important for any assumed heat source, but especially so for electrical or solar heating (*Sonett and Reynolds,* 1979). Because of their higher metal content, H chondrites have lower heat capacities and higher electrical and thermal conductivities than L and LL chondrites (*Wood,* 1963). Within the LL3 chondrites, *McCoy et al.* (1990) recently found that metallographic cooling rate increased with TL sensitivity, which they interpreted in terms of differences in thermal conductivity between one LL parent object and another. In that case, differences in degree of compaction, rather than metal content, were involved.

There is no evidence that H chondrites formed before the other classes. Assuming that the apparent I-Xe ages reflect true ages, and not I heterogeneity, then ordinary chondrites formed over a 60-Ma period with no apparent systematic difference in the time of formation between H and L chondrites (*Swindle and Podosek,* 1988). It also seems that the timescale of formation was much greater than the half-life of ^{26}Al. Similarly, there is no evidence that H chondrites came from greater burial depth than the other classes. The proportion of chondrites that are brecciated is greater for the LL chondrites than for the H and L chondrites, which may imply a location nearer the surface [*Binns* (1967) found that 66, 20, and 33% of the LL, L, and H chondrites were brecciated, respectively]. On the other hand, gas-rich regolith ordinary chondrite breccias are predominantly H chondrites [23 out of 30 in *Wasson's* (1974) compilation]. *Rubin et al.* (1983) have discussed physical scenarios that might explain these observations. Cooling-rate data for type H3 chondrites are very meager; all cooling rates are subject to many uncertainties and all three classes show considerable spread. However, metallographic cooling rates for chondrites of all petrographic types indicate that H chondrites tend to have higher cooling rates than L and LL chondrites (Fig. 7). These data might also indicate that cooling rate is related to metamorphic intensity through the physical properties of the class, rather than through burial depth.

SUMMARY AND CONCLUSIONS

Induced TL data are presented for 125 type 3 ordinary chondrites. The data confirm pairing suggestions for meteorites from the Allan Hills region of Antarctica, although it is possible that the major ALHA77011 fall suggested by *Scott* (1984b) is actually two discrete falls. While there probably is widespread pairing among the L3 chondrites from the Lewis Cliff region, it is unlikely that they are all paired and it is difficult to identify specific pairing groups. For 77 of the present samples duplicate chips were run. For 67 of these, the agreement between the chips was within a factor of 3, the nominal uncertainty due to sample heterogeneity and weathering. Seven of the remaining samples are known or thought to be gas-rich regolith breccias, and for an additional five there is petrologic evidence for brecciation, so it is assumed that, in general, disagreements between splits of a factor of >3 are due to brecciation. We conclude that the volatile-rich type 3 chondrites identified by *Anders and Zadnik* (1985) are breccias containing volatile-rich clasts, and not themselves especially primitive.

The present induced TL data, olivine heterogeneity, carbon content, and inert-gas content have been used to assign the present samples to petrologic types. Twelve meteorites of type 3.0-3.2 have been identified, including LEW86134, Y74660, and Semarkona, which are type 3.0. Ten of the breccias contain material that may also be type 3.0-3.2.

The temperature and width of the induced TL peak are also related to thermal history, in confirmation of earlier work (*Guimon et al.,* 1985), with type 3.2-3.4 chondrites tending to have narrower peaks at lower glow curve temperatures than the type 3.6-3.9 chondrites. If this behavior is associated with feldspar disordering (*Guimon et al.,* 1985), then metamorphic temperatures for type 3.5 were probably on the order of 500°-600°C. This value is in reasonable agreement with other estimates of metamorphic temperatures for type 3 ordinary chondrites.

Type 3 H chondrites tend to be higher petrographic type than the type 3 L and LL chondrites; with one exception, H chondrites are type >3.4. There appears to be no evidence that H3 chondrites formed earlier than the L3 and LL3 chondrites, or that H3 chondrites came from greater depths in their parent bodies than the L3 and LL3 chondrite, and it is concluded that the lower heat capacity, higher thermal or electrical conductivity of H chondrites, caused by their higher metal content, resulted in a different thermal history.

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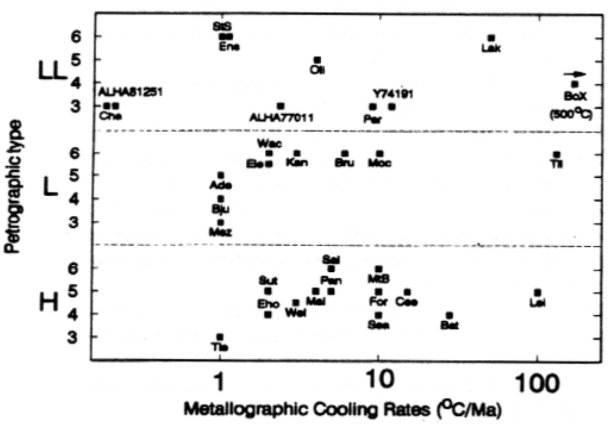

Fig. 7. Plot of petrographic type against metallographic cooling rate for 31 ordinary chondrites (data from *Wood,* 1979; *McCoy et al.,* 1990).

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